Mars Pathfinder Lander
Deployment Mechanisms

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Abstract

The Mars Pathfinder Lander employs numerous mechanisms as well as autonomous mechanical functions during its Entry, Descent and Landing (EDL) Sequence. This is the first US lander of its kind being an unguided, airbag-protected, non-soft landing using airbags instead of retro rockets to soft land. The arrival condition, location, and orientation of the Lander will only be known by the computer on the Lander. The Lander will then autonomously perform the appropriate sequence to retract the airbags, right itself, and open such that the Lander is nearly level with no airbag material covering the solar cells. This function uses two different types of mechanisms, the Airbag Retraction Actuators and the Lander Petal Actuators which are designed for the high torque, low temperature, dirty environment, and limited life application, The development of these actuators investigated low temperature lubrication, Electrical Discharge Machining (EDM) to cut gears, and gear design for limited life use,

Summary

The complex EDL sequence begins with a cruise stage separation at 8500 km altitude and 6100 m/s (13,645 mph or Mach 18 at one atmosphere). After the deployment of a parachute and the descent of the Lander on a 20 m long bridle, the airbags inflate seconds before RAD firing and bridle separation. The Lander strikes the surface at roughly 22 m/s (50 mph), 35 minutes after cruise stage separation. After bouncing as high as a nine story building and continuing to bounce for one to fifteen minutes, the Lander should come to rest somewhere in the Ares Vallis in southern Chryse Planitia on Mars on July 4, 1997. The airbags will be covering the outside surfaces of the Lander, but may be ripped and deflated or may be intact and partially inflated.

Upon coming to rest, the Lander must autonomously determine its attitude and condition and perform the actions required of the Airbag Retraction Actuators (ARA) and Lander Petal Actuators (LPA) to flip the Lander over, if needed, and open upright on the surface of the planet. The Mars Pathfinder Lander Retraction and Deployment Sequence was developed to solve some challenging and diverse technical requirements. The Lander is a tetrahedron, roughly one meter in diameter. it consists of a triangular base petal with three similar triangular side petals. (Figure 1) Each of the four petals is protected during impact with Mars by a large 6-lobed airbag made out of Vectran fabric (similar to Kevlar). The final resting state of the Lander is random, most likely coming to rest on the rocky surface with one of the four petals down. At this point, the airbags are slightly limp and draping over the petals.

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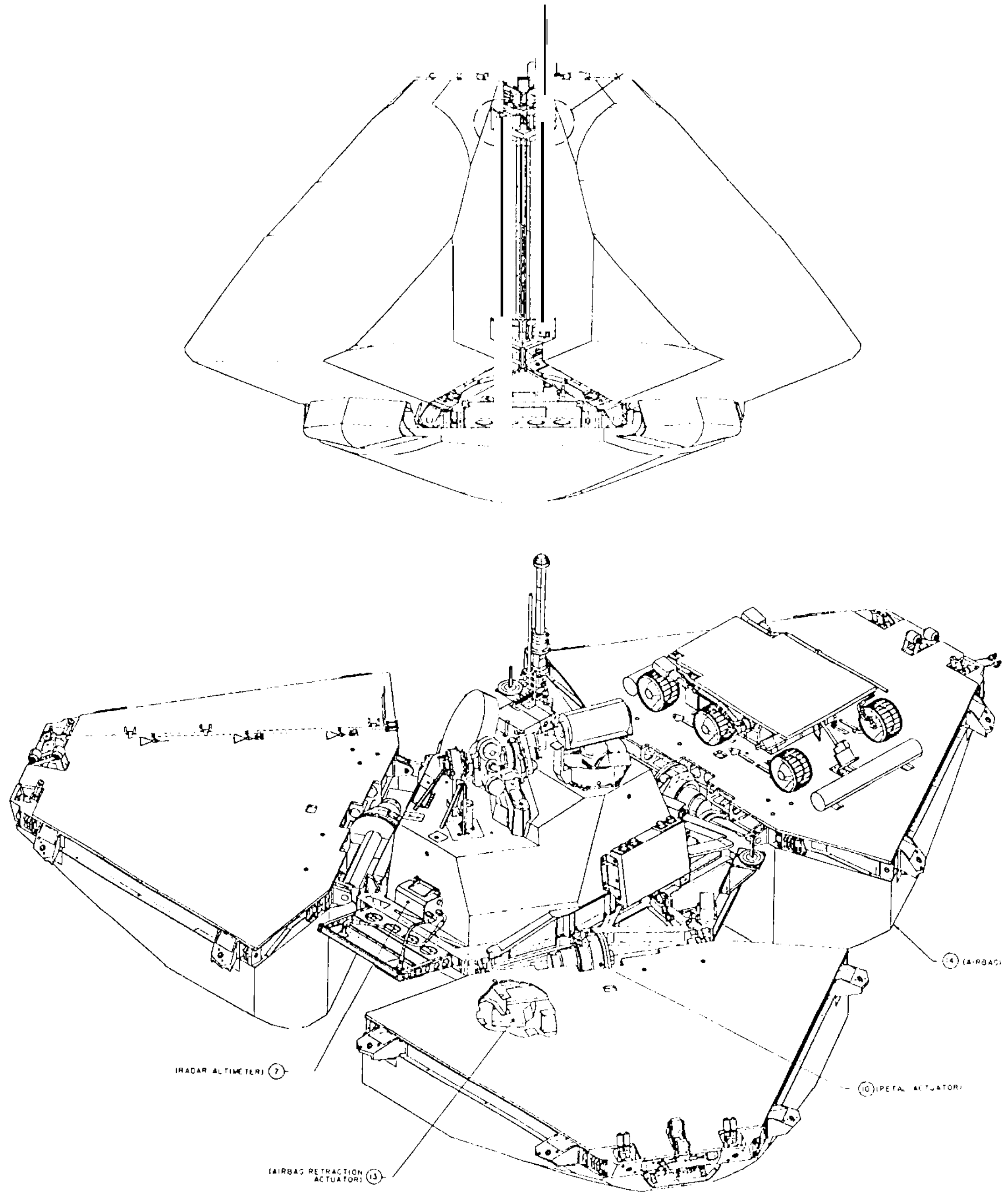


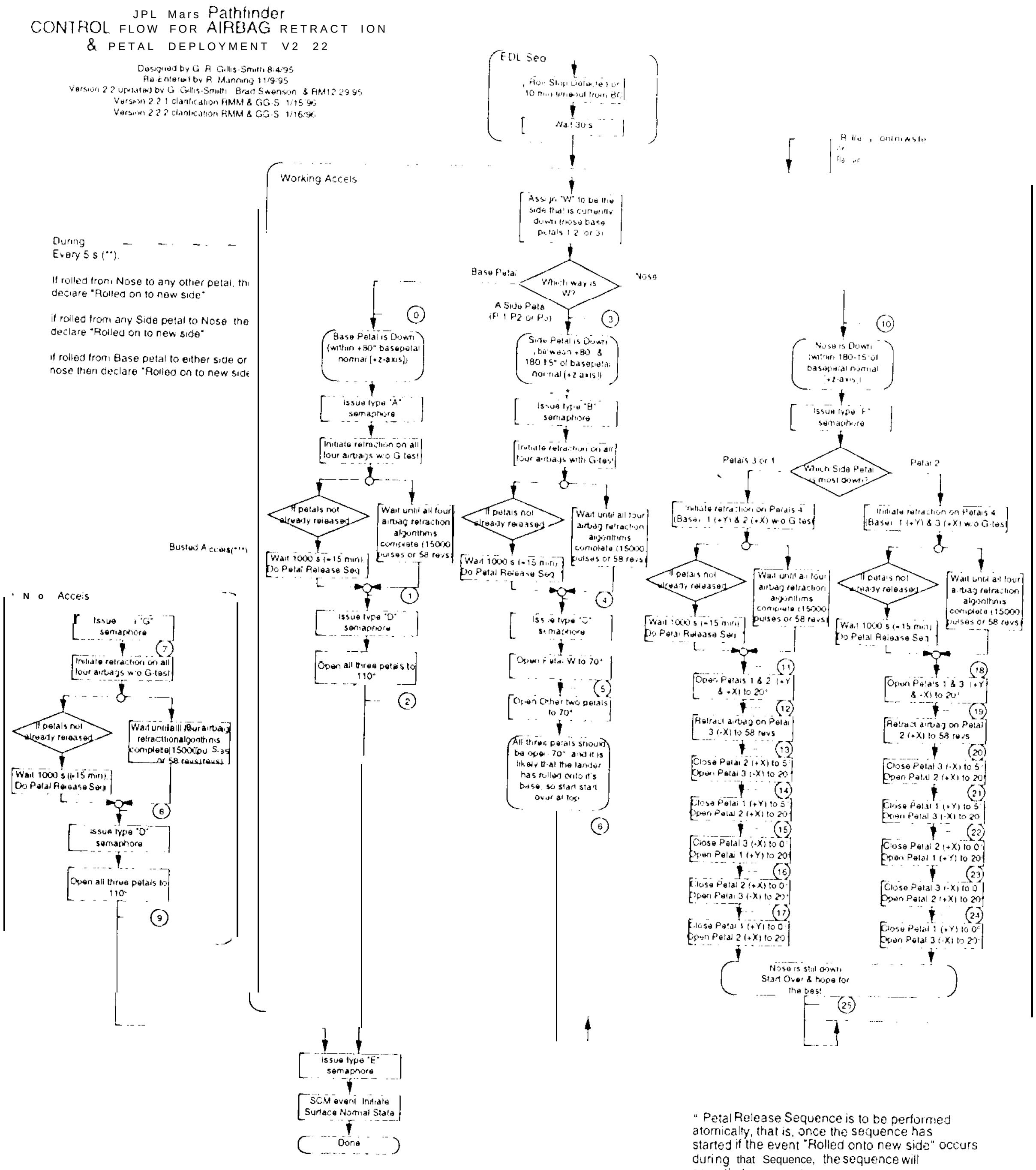
Figure **1** Mars Pathfinder Lander Stowed and Deployed

Sequence

Since the antenna used to communicate with Earth is located inside the closed Lander, the sequence must be completely autonomous and able to respond to the unknown landing configuration. Also, it must not give up or get into a dead end or infinite loop, and yet be simple enough that it can be tested. This was accomplished by first determining which of three basic orientations the Lander is in: base down, side (any one of three) down, or nose down. See Figure 2 for the flow chart of the Sequence. Each of these conditions requires a specific sequence to optimally retract and deploy. However, if the accelerometers or motor encoder telemetry should ever fail, the sequence must still enable the Lander to get upright and open. This is done by retracting all bags and deploying all petals. This results favorably, but the bag material sometimes covers pacts of the solar cells. Nominally for a side-down condition, the Airbag Retraction Actuators retract the three of the four bags that the Lander is not resting on. In doing so, the retraction cables inside the bags act like draw strings to simultaneously open vent patches and cinch the bags. Five retraction cables, each about 5.7 m (224 inches) long, are retracted onto a spool inside the ARA. After the bags are retracted, the Lander again senses the gravity vector and begins opening the petal that is on the bottom by turning on the appropriate Lander Petal Actuator, followed by the other two petals. This is done to minimize the moment of the flipped mass and protect the science payload. The final state is to have all four petals coplanar allowing the camera to take pictures, the communication link with earth to be established, and the Rover to drive off of the petal. Lander leveling is possible if required.

The least likely orientation is to have the Lander balanced on the top of the tetrahedron. This orientation is remarkably stable on level ground and creates a great challenge to move the center of mass over the pivot point. This is actually achieved with the use of the airbags. The airbag on the petal that the Lander is leaning towards is left unretracted while the other bags are retracted in order to bring them in close to the Lander e.g. The two petals opposite the unretracted bag are opened only 20° so they are 90° to the base petal and hence the tallest they can be and then the final bag is retracted. The drag force of the bag is usually sufficient to pull the Lander over onto its side which initiates the sequence to restart to use the side-down option.

Testing of the Sequence was performed on a full-scale, Mars-simulated terrain at ambient temperatures and in a vacuum chamber without rocks or terrain at Mars temperature and pressure (-100° C and 8 torr). It was found that even at earth-weight the Sequence was successful every time under normal and nominal worst case conditions while only manually created “impossible situations” would result in failure.



Semaphore Type Meanings
A. Base Petal Down
B. Side Petal Down
C. Some Bags Retracted
D = All Bags Retracted
E. All retracted and petal depoyment complete
F = Nose down
G. Busted Accels

* Petal Release Sequence is to be performed atomically, that is, once the sequence has started if the event "Rolled onto new side" occurs during that Sequence, the sequence will nevertheless complete

** Some persistence is required for the detection of the event 'Rolled onto new side. To reduce chatter the event should only be issued if a new side is detected and stays valid for at least 25 Seconds (5 samples every 5 s)

*** The "Busted Accels' event will on be issued if the accels are deemed "broken" after 5 attempts (spaced every 5 seconds)

Figure 2 Airbag Retraction and Petal Deployment Sequence Flow Chart

Airbag Retraction Actuator

The Airbag Retraction Actuator is a robust winching mechanism used to retract each of the four large airbags on the Mars Pathfinder Lander. The primary design criteria for the actuator was a high-torque, compact, and lightweight design. The mechanism employs two DC brush Maxon motors, each driving 1550:1 five-stage planetary gearboxes, which both drive a single cluster spur gear, which drives a secondary spur gear and spool assembly, resulting in an end-to-end 8277:1 gear ratio. (Figure 3)

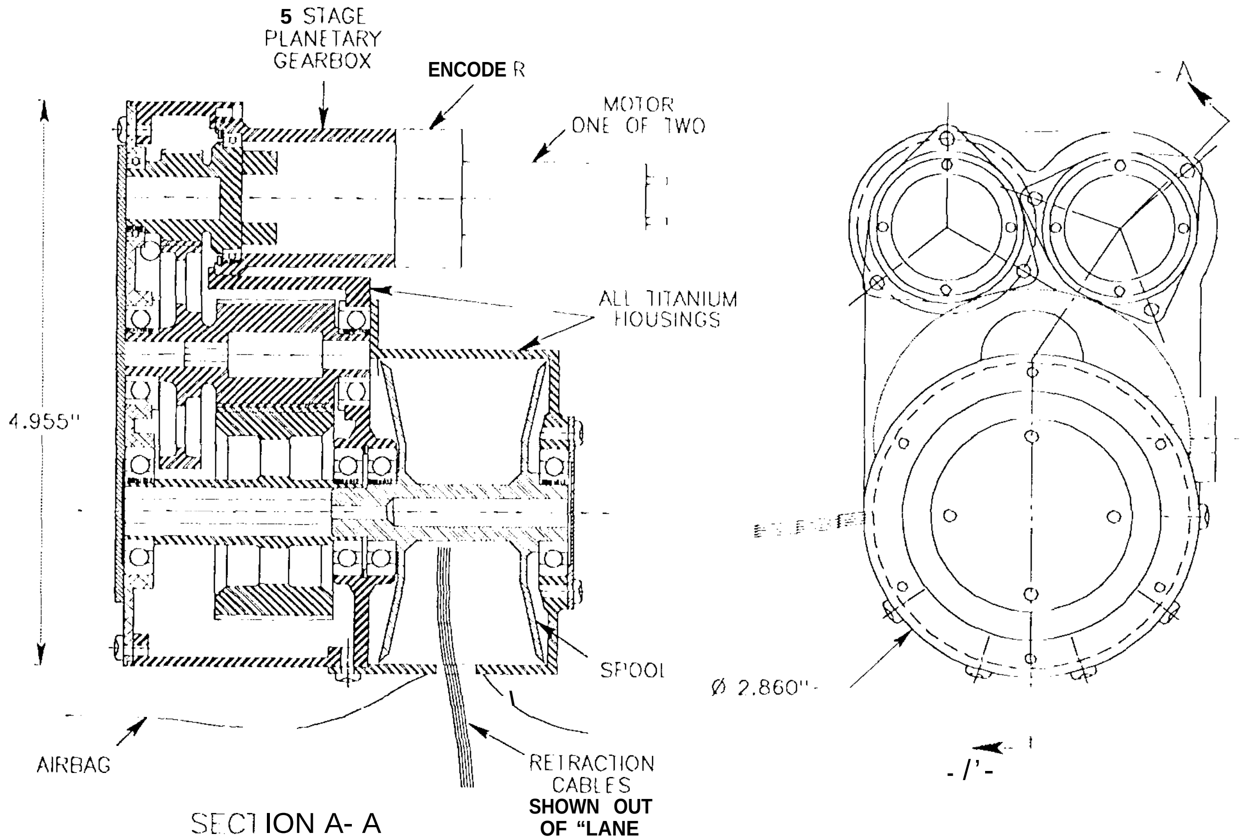


Figure 3 Airbag Retraction Actuator

Each of the motors has a stall torque near 15.8 mNm (2.24 in-oz). One of the two motors in each actuator has an optical encoder between it and the planetary gearbox in order to record motor revolutions and hence the length of cable retracted. The five-stage planetary gearbox was designed such that the ring gear and output can be customized and used in any other actuator, (Figure 4)

This gearbox with a custom ring gear and output feature was used in the gimble of the Imager for Mars Pathfinder and will be used in a robotic arm of a 1998 Mars lander mission. For the ARA, the fifth-stage planet carrier is a bearing-supported pinion gear that drives the cluster gear. The final output stall torque of each motor/gearbox is about 11,3 Nm (100 in-lb). The total output stall torque of the ARA is about 96 Nm (850 in-lb) at temperature. (Figure 6)

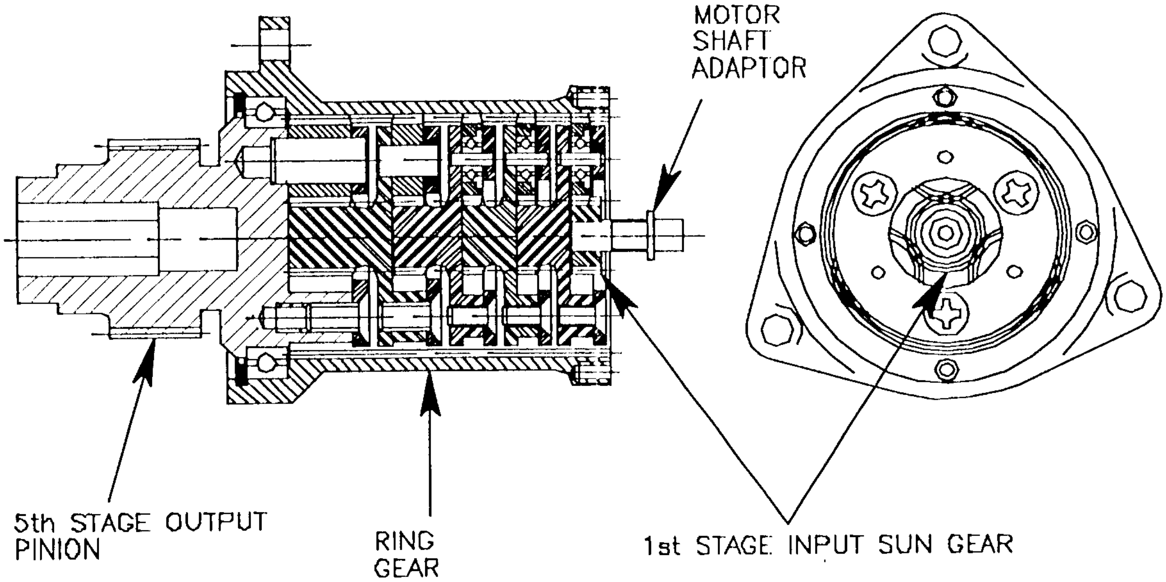


Figure 4 ARA Five-Stage Planetary Gearbox

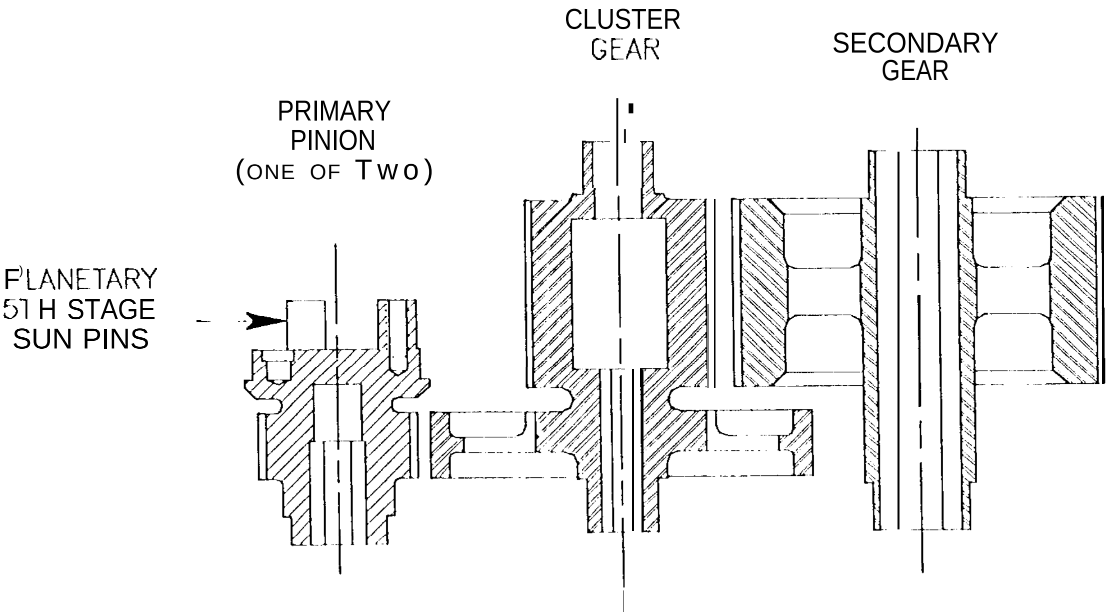


Figure 5 ARA Gears

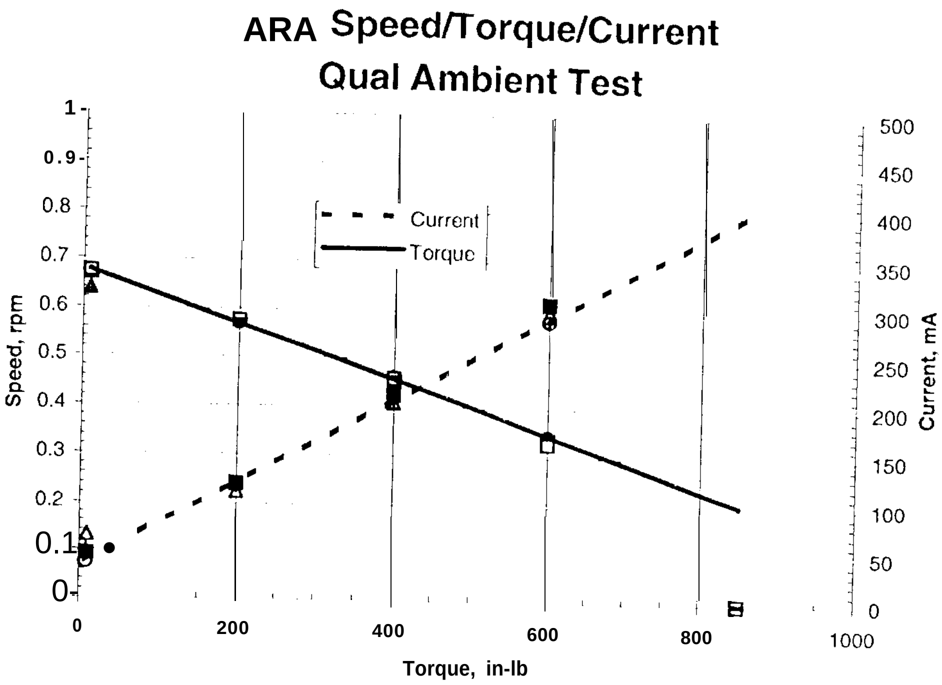


Figure 6 ARA Speed/Torque Curve

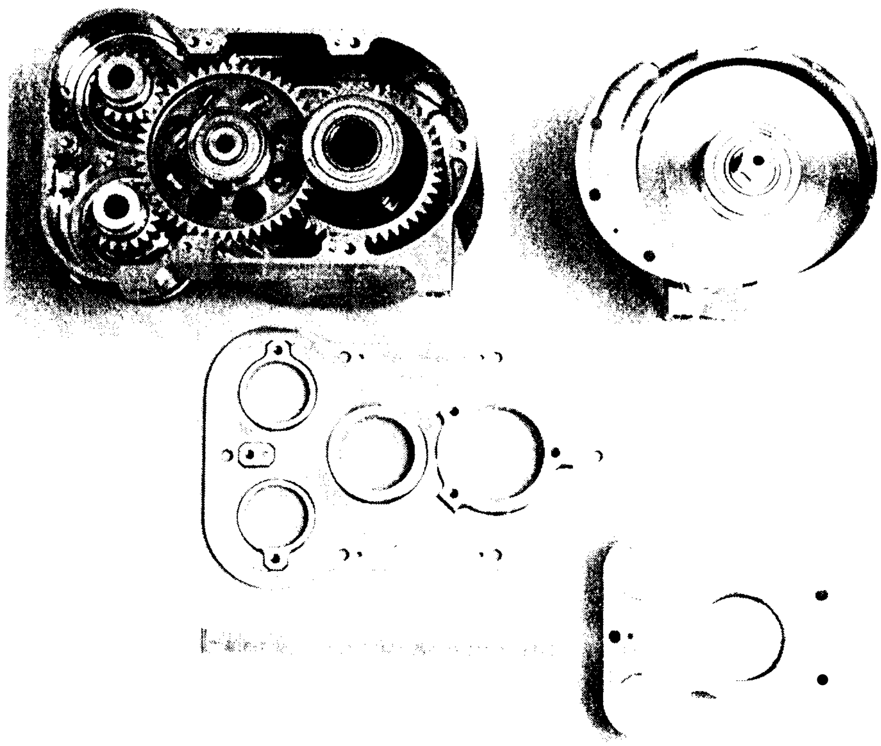


Figure 7 ARA Assembly

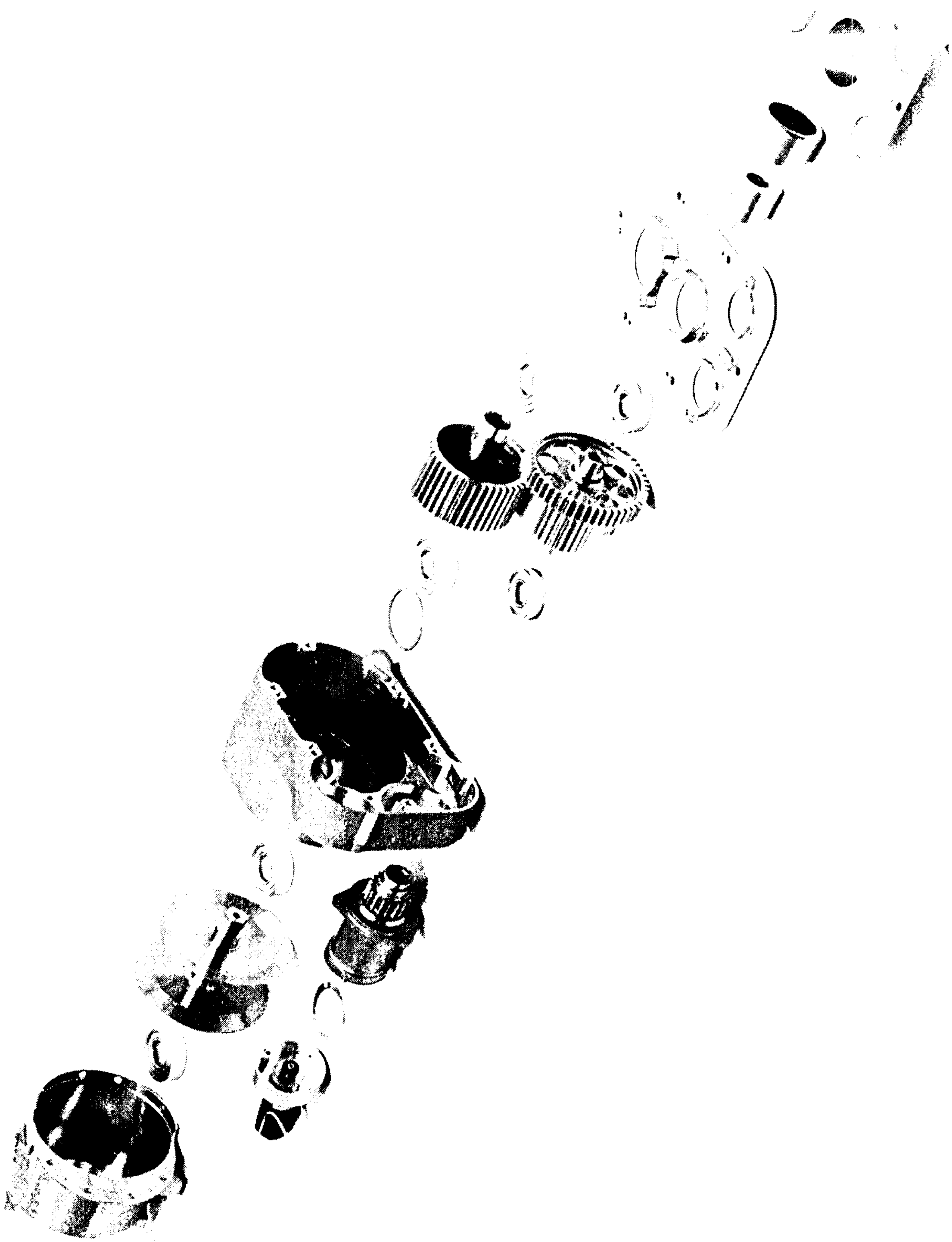


Figure 8 Airbag Retraction Actuator Exploded View

Nedox plating on gears and Bray 604 grease breakdown:

The primary 5-stage planetary gearbox was designed and built by American Technology Consortium. They made the first two prototypes with the ring gear and planets plated with Nedox, a electroless nickel/Teflon matrix for its great wear properties. Due to Bray grease 604, which contains Bray oil 814, having superior low temperature performance and being used at low temperature in Mars Pathfinder Rover Actuators, it was used in the two prototype gearboxes. Upon testing the first of the two prototypes, the performance degraded and became more erratic. It was later determined that the hard Nedox coating had suffered sub-surface delamination on the last two stages and the Bray had turned to a hard tar-like substance. (Figure 9) The study of what caused the Bray to break down included researching the Lewis Acids phenomenon and the impact of nickel particles in the gearbox. Lewis Acids act as catalysts to cause a breakdown of the oil in Bray grease, even at low contact pressures, It was found that the 814 oil in the Bray grease was not robust enough for the high contact loads at the asperity level and that the Nedox particles probably added to the high local loading. High contact loads cause the oil breakdown quickly, resulting in identical results as a breakdown catalyzed by Lewis Acids. Visually, one cannot determine whether the grease was a mechanical breakdown or one catalyzed by Lewis Acids at lower loads. By eliminating the Nedox plating and choosing a grease with more robust oil and molydisulfide (Bray 602), the gearbox experienced no degradation after repeated heavy testing at temperature. Bray 602 was selected because it is basically Bray 600, which contains Bray oil 8152, with molydisulfide added for extra load-carrying ability and lubricity. It has similar low temperature torque properties as Bray 601.

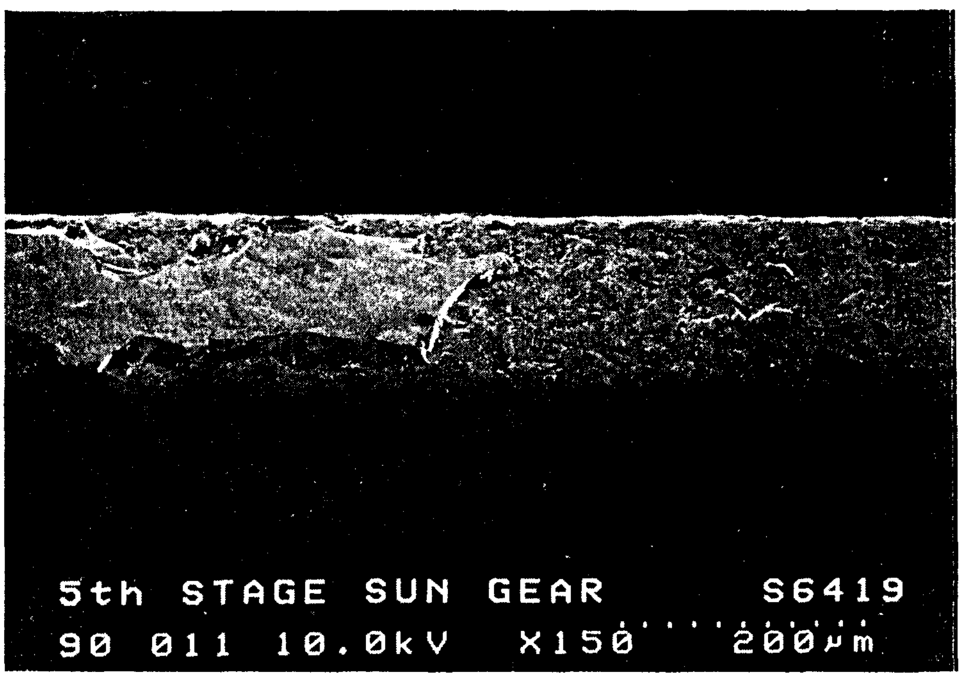


Figure 9 Nedox Failure on Tip of Gear Tooth

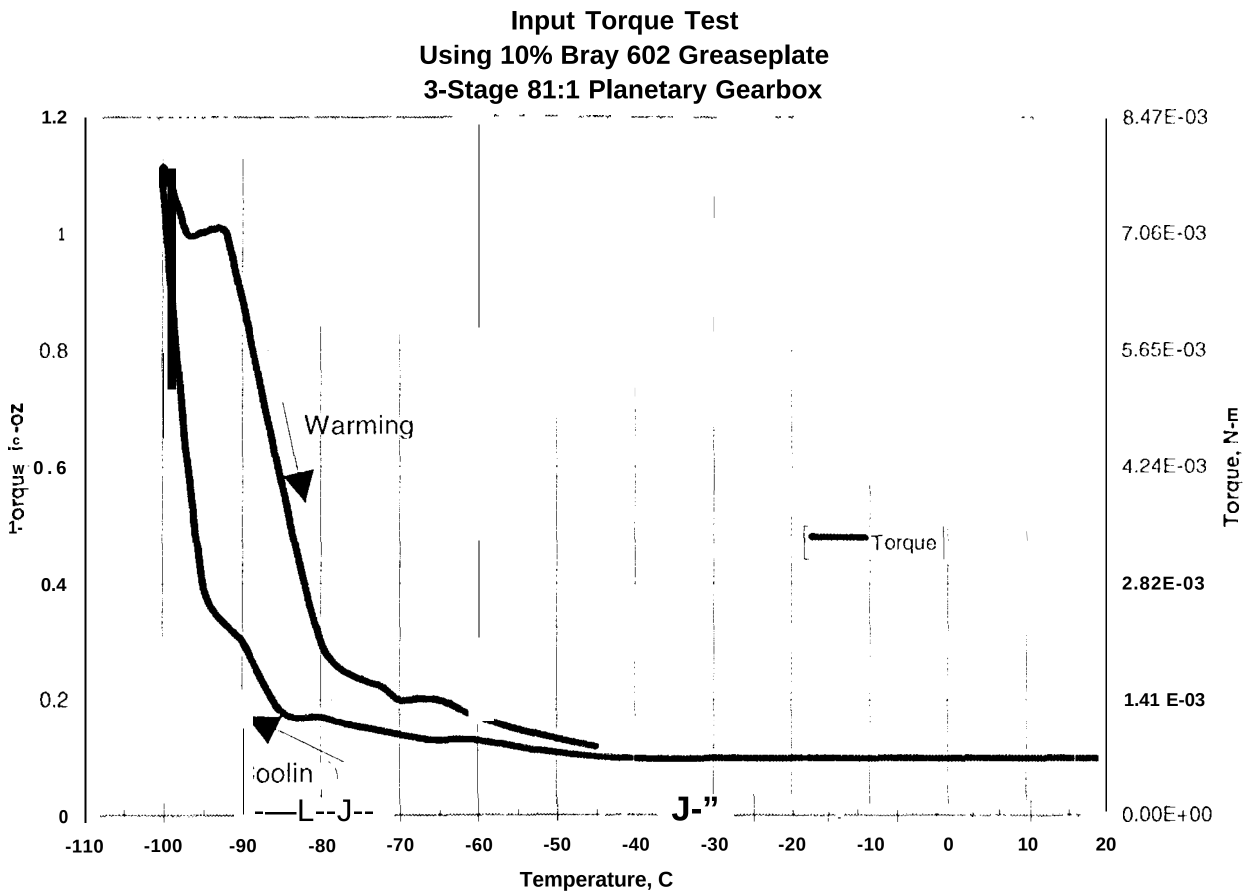


Figure 10 Grease Viscosity

Low temperature testing of Bray 6_02 grease:

In order to determine the effects of low temperature on Bray 602, a quick test was done using three of the five stages of the ARA primary gearbox. The gearbox was cleaned and then grease plated using a 10% grease, 900/. Freon TF solution and mounted in a cold box with the primary stage open to the top. The primary sun gear was pressed onto a long insulating shaft, driven by a torque watch. The temperature was slowly dropped and the torque required to turn the input sun gear was recorded. (Figure 10) The hysteresis in the torque plot is believed to be due to temperature lag in the grease in the center of the gearbox. It could safely be assumed that the knee in the curve for this grease is about -75° to -80° C with almost no changes in drag effects from ambient to -75° C but 10-fold increases from -75° C to -95° C. This test determined that the lowest acceptable flight allowable temperature limit is -75” C, requiring heaters to maintain a safe temperature of -55° C.

EDM used to fabricate gears out of maraging steel:

A new technology that makes the ARA interesting is that the gears were produced using the wire and sinker Electrical Discharge Machining (EDM) process. This allows for infinite adjustment of gear tooth form and shape without the need for custom bobs or shapers or new master gears for each new tooth form, The reason this technology was first explored is that the loading application was quite high and would require a tough material. The material selected, Maraging Vascomax C300, is usually heat treated after final machining to obtain a yield strength greater than 2000 Mpa (290 ksi) along with good toughness properties, The challenge is that the material shrinks during heat treat, deforming the gear, and the material is strengthened beyond the capabilities of normal hob and shaper processes. With EDM, the material can be heat treated prior to cutting the gear forms and final machining, allowing the part to have a perfect, as-cut gear tooth. Concerns of a re-cast layer that would weaken the tooth contact surfaces have been investigated. McLaren Formula 1 racing team uses EDM to manufacture their transmission gears in order to customize each gearbox for each race, They do, however, only use a set of gears once and then dispose of them.

In using EDM to machine the spur gears it was found how important very accurate tooling is to produce a gear with excellent form and surface properties, The gears used in the ARA were designed to have an optimized toothform for high load carrying capability for a limited life at peak loads. If the output gear were designed for infinite life, the face width would have been more than 4 inches for a 1 inch pitch diameter. This diameter was reduced to .917 PD and a face width of only 1 inch, but the tooth form was modified and had a 25° pressure angle. Instead of fabricating custom bobs, shapers and master gears, EDM was selected to make these custom gears, A company was selected for their experience in high precision EDM, but they had never made gears before. Using software written to produce gearforms, the gear data was entered in and a test gear wire cut. This test gear was sent to a facility to analyze tooth form, surface condition, and tooth thickness. They found that the tolerances held were that of a AGMA class 10 gear, but one tooth was thicker than the rest. After researching the EDM gearform software and the tooling used, it was discovered that the tool was not symmetric. After correcting the tooling, the flight gears were made. A second challenge came in that only two of the four gears could be made using wire EDM, but the other two had to be done with a sinker electrode. The electrodes were cut on the wire EDM machine allowing for wire thickness offset. Premium grade, fine grain graphite electrodes, one roughing followed by two finish, were used to produce gears of exceptional form and surface, with tolerances that of a AGMA class 10 gear.

The recast layer is the outermost surface that has been remelted and weakened by the heat of the cutting process. The concern about recast layer was addressed and found that the type of power supply and the way the part is cut has “reduced the recast to an almost inconsequential degree.” [1] Additionally, electrolysis has been found to be a contributing factor in weakening parts made with EDM. The type of power supply used to cut the ARA gears is called an AE or Anti-Electrolysis supply, a proprietary system of Mitsubishi. A DC power supply used in EDM has good machining speed, but electrolysis is high and produces more heat in the workpiece causing more thermal damage. Using an AC power supply can improve the surface finish and integrity, but the speed is half that of the DC system. In each AC cycle, one pulse chemically removes ions from the workpiece, while the pulse of opposite polarity removes less material, but does not remove ions by electrolysis. "Even though (the) surface finishes are improved, we still have an electrolytically damaged workpiece, however lessened. This can be in the form of cobalt depletion, rust, oxidation, hydrogen embrittlement, etc." [1] An Anti-Electrolysis (AE) generator capitalizes on the benefits of DC and AC systems, but eliminates the disadvantages. The AC signal is rectified such that all of the negative pulses were flipped up to be positive pulses. What is achieved is a machining process that is fast and produces parts that are stronger and have improved surface finishes. In the case of the gears used in the ARA, the microfinish was measured to be better than 24 rms. The inspection data for a 48 tooth gear that was cut with wire EDM and an 18 tooth gear that was made with a sinker electrode shows the variance from perfect tooth form. The average variance is .007 mm (.00028) for the wire-cut and .013 mm (.0005) for the sinker, It was found that there was about .007 mm (.00027) taper on the sinker-made gears, These tolerances are roughly equivalent to a AGMA class 10 gear,

One other benefit of using EDM to machine the gears was that the cores of the gears needed to be lightened, so they were wire cut with an internal hex bore, (Figure 7) This made **dyno testing easy since a hex shaft adapter could be placed into any of the** gears during actuation to speed/torque test the actuator at any of its stages.

Lander Petal Actuator

The Lander Petal Actuator (LPA) is a large, 5.7 kg (12.5 lb), high-torque, mission-critical mechanism used to flip over and open the 330 kg lander. The primary design criteria for this actuator was ultra high torque (12,000 in-lb) in a small package with minimal mass, (Figure 11) Output speed was a secondary requirement to be less than two hours for both retraction and deployment. Electronic commutated, brushless DC motors were selected because of their high torque, higher reliability, and because one was already being developed for another project. The motor has a 0.14 Nm (20 in-oz) output stall torque driving a three-stage 49.3:1 spur gearhead. This motor/gearhead drives a 4:1 internal spur gearset inside the LPA. This outputs through a detent clutch to a 160:1S-tooth Harmonic drive limited by a maximum (ratchet) torque of 1580 Nm (14,000 in-lb)! Torque is transmitted to one hinge per petal via a titanium tube with square drive holes in each end. The output speed of this 31,552:1 actuator is about 40 minutes per revolution, The operating temperature of the LPA is -40° to +35° C and was tested to -55° and +55° C with little change in speed/torque characteristics. See Figure 13 for the speed/torque curve, This correlates with the findings from the ARA primary gearbox test which found that the Bray 602 viscous drag characteristics behave linearly down to -75° C. Kapton film heaters were incorporated into the flight design of the LPA to maintain the actuator above -40° C.

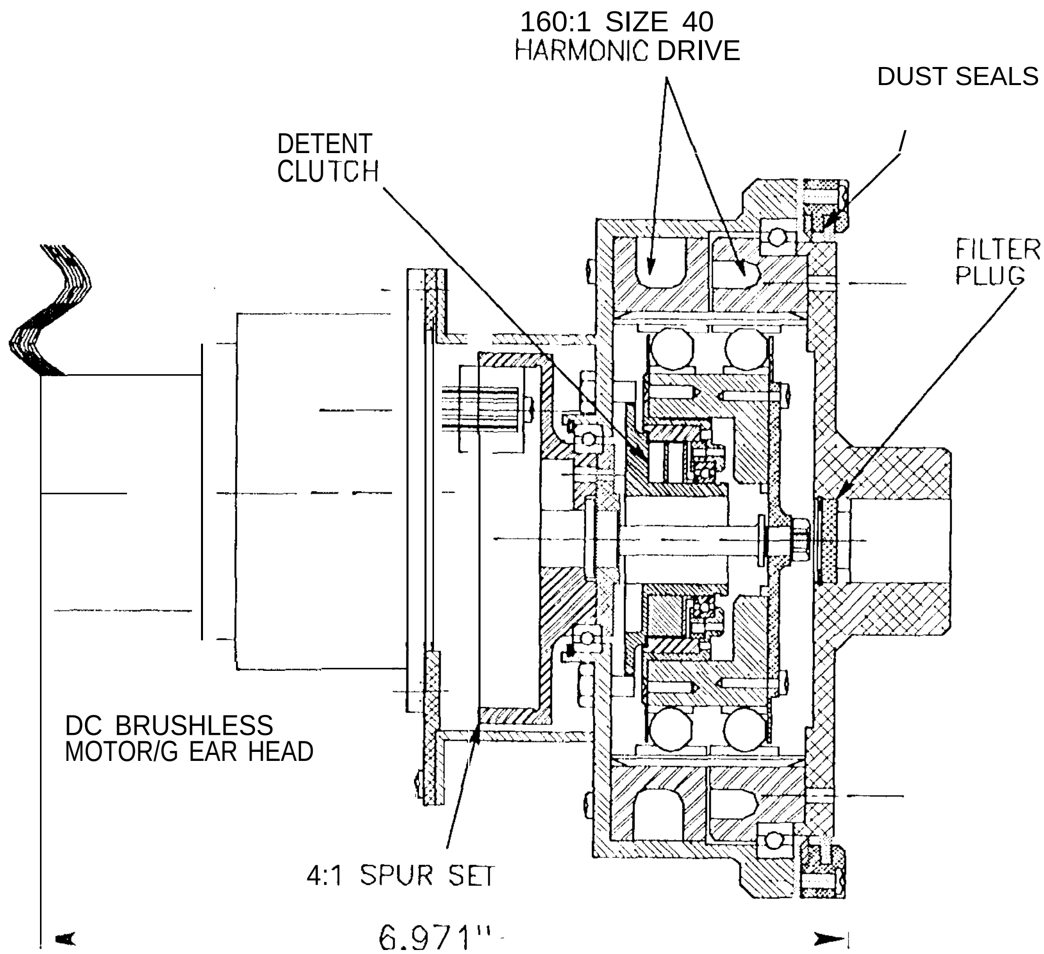


Figure 11 Lander Petal Actuator

Detent Clutch:

The clutch is driven continuously between the input to the wave generator and the housing when the actuator is powered. The purpose was to create enough backdrive torque to support the weight of the lander when the actuator is turned off. It uses 4 opposing pairs of small compression springs pressing on rollers that ride on the internal surface of a toothed ring gear, The advantage of such a clutch is that its torque limiting performance is fairly independent of vacuum and temperature conditions and the running torque is slightly lower than the breakaway torque of about 1,36 Nm (12 in-lb).

Dust Protection;

Several protective measures had to be implemented in order keep the abrasive Martian dirt out of the actuator. The dust seals use both an outer felt seal and an inner Vespel wiper. The actuator must vent upon launch and refill upon landing, so a porous metal plug was incorporated in the drive hub to allow air passage without dirt. (Figure 11)

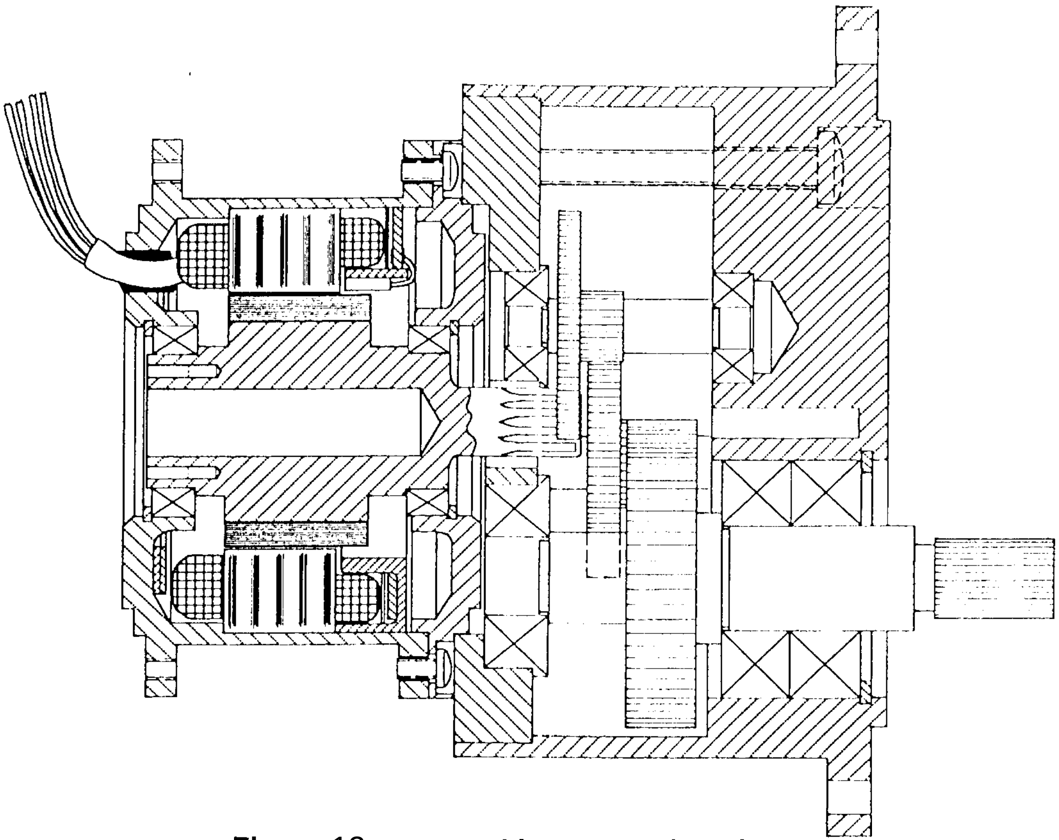


Figure 12 **DC Brushless Motor/Gearbox**

Harmonic Drive:

The S-toothform Harmonic is able to transmit more torque than the standard toothform due to more tooth contact area. (Table 1)

Table 1 Comparison of Toothform Torque Capability

Catalog Rating	Size 40 Standard	Size 50 Standard	Size 40 S-Tooth
Ratchet Limit	745 Nm 6600 in-lb	1410Nm 12,490 in-lb	1580 Nm * 14,000 in-lb
Momentary Peak Limit	Ratchet Limited	Ratchet Limited-”	1370 Nm 12,150 in-lb
Mass (unlightened)	3.0 kg	6.0 kg	3.0 kg

* Tested value

The new S-tooth enabled the use of the lighter and smaller size 40. It was found through dyno testing that the size 40 Harmonic would generally ratchet the flex spline gears before the motor would stall. This is undesirable, but was deemed acceptable because the torque output **would be limited to the value necessary to lift the Lander.** These actuators were dyno tested by attaching the actuator to a .61 m (24 in) diameter pulley, 4 m high on a static test tower and lifting stacks of steel weights. Cold operation was achieved by filling a purged Styrofoam box with liquid nitrogen and cold nitrogen gas and warmed again with a gas heater.

The circular splines exhibited acceptable performance after lightening from 1.02 kg (2.25 lb) to roughly .68 kg (1.5 lb), much to the amazement of the Harmonic vendor. The wave generator was hollowed out to make room for the detent clutch and allow the actuator to be much more compact.

Low Temperature Application of Harmonic Gears:

Due to Harmonic gears being only 30-45°/0 efficient from their characteristic sliding friction they are sensitive to temperature effects on lubricant. The motor on the LPA only produces .141 Nm (20 in-oz) at stall. For another application on Mars Pathfinder, a similar motor with half the stall torque was used to drive a size 10 Harmonic drive directly. This actuator would not run below -50° C. The lubricant was changed to a very light grease plate of Bray 604 with Brayco 814 low temperature oil, which corrected the cold operation problems. With 800 times the input torque to a size 40 Harmonic gear that was filled to 10 to 20% of the Bray 601, there were no problems to -100° C. The obvious lesson is that when using smaller, lightweight, low-torque motors the torque needs to be '(preamplifier" before being transmitted to the less efficient Harmonic gear.

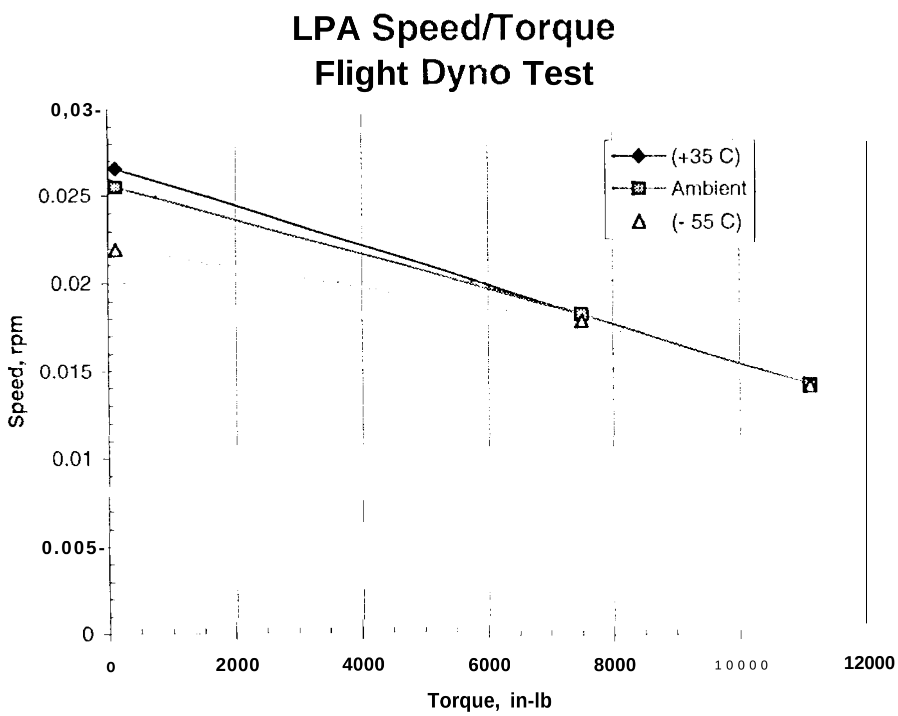


Figure 13 LPA Speed/Torque Curve

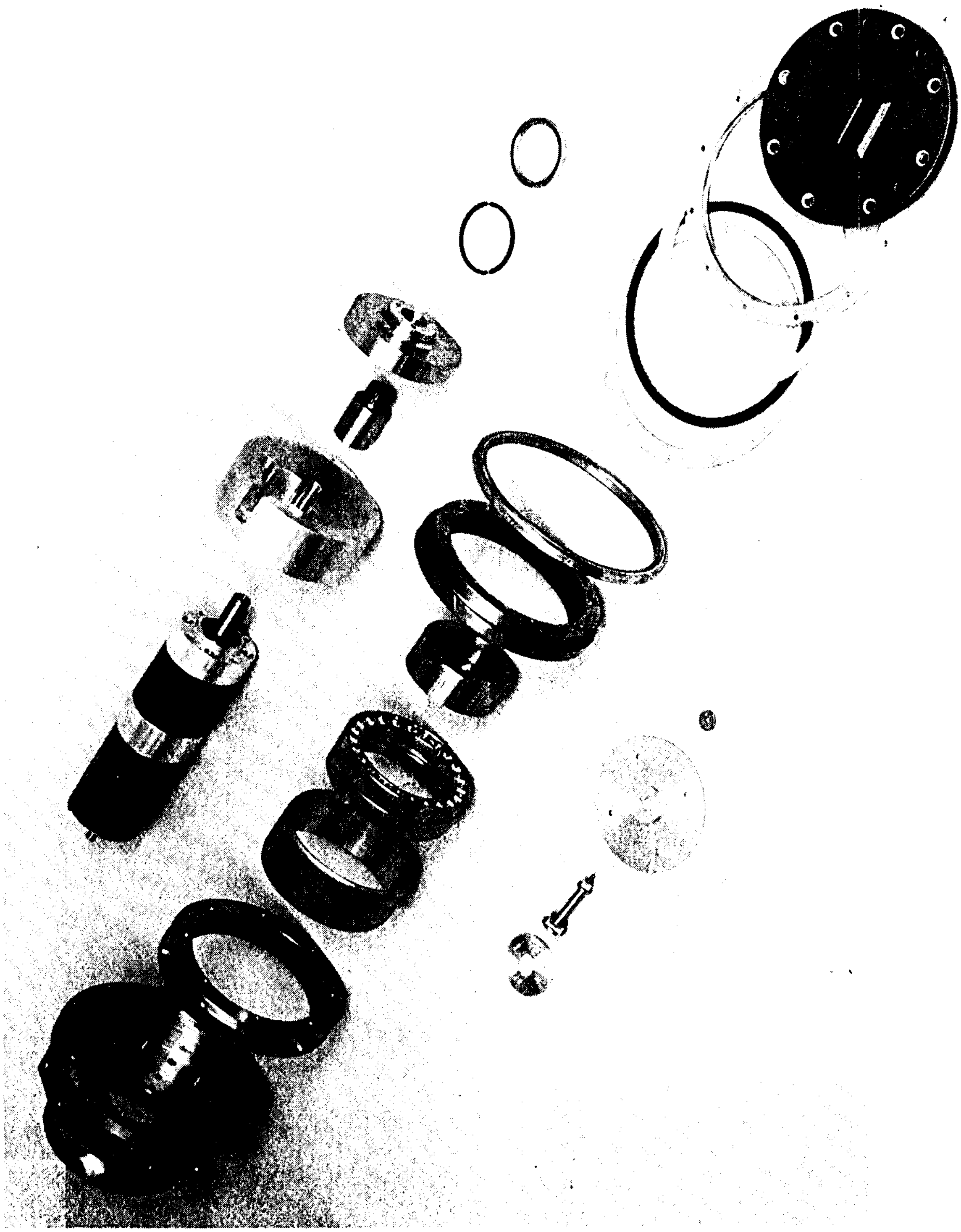


Figure 14 Lander Petal Actuator Exploded View
(with test motor and no clutch)

Conclusions

The mechanical failure of the Nedox causes us to conclude once again that gears under any significant load should not be plated with any hard material. Sub-surface delamination occurs due to the “ceramic-coated banana” condition. Repeated loading and deformation of the gear teeth causes the hard, non-wearing coating to flake off, now becoming “ground-up razor blades” in the gearbox. For small, lower-torque **gearboxes this proves catastrophic.**

Bray grease, such as 604 that uses the Brayco 814 oil is susceptible to mechanical breakdown under moderate loads, especially in conjunction with particles that cause high loading and heat at the asperity level. Those that use the Brayco 815Z oil, such as 600, 601 (with rust preventative), and 602 (with molydisulfide) are more robust for contact loads, but still should avoid high loading or particulate contamination.

Bray 602 tends to be fairly linear in viscosity from ambient temperatures down to -75° C, but has geometric increases in viscosity and hence torque loss below -75° C.

Electric Discharge Machining (EDM) is an acceptable machining technique for gears, provided the surface has not been adversely impacted by the process, It appears that the AE power supply enables the EDM process to produce stronger parts with better surface finish. At this time, though, it would be prudent to use gears made with the EDM process for limited life applications until more life testing is possible.

Due to the high startup drag torque of Harmonic gears, it is imperative to use other types of gears to “preamplify” the torque before it is transmitted to the Harmonic.

Some DC brush motors may be used reliably in a space environment, but must be free of grease lubrication at low temperatures. Extensive dyno tests on one type of small, DC brush motor proved reliable operation to -75° C provided all of the grease was cleaned out.

Acknowledgments

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References

1. Guitrau, E. “EDM and Electrolysis.” E & M Engineering. 1995.